

Stochastic modeling of stormwater and receiving stream concentrations

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ABSTRACT: A stochastic approach was developed and applied to the Butte, Montana hillside abandoned mining site for modeling stormwater runoff and subsequent receiving stream loadings. This approach enabled capture and quantification of the uncertainty associated with stormwater quality data and allowed the prediction of copper and zinc concentrations caused by runoff from the Butte hillside during storm events. Runoff flows were generated in a spreadsheet model using the rational method and stormwater concentrations were input as probability distribution functions (PDFs). Correlations between sampling sites were also incorporated into the model. The PDFs were combined with runoff hydrographs and stochastically modeled using Monte Carlo simulation. Stream loadings predicted by the model PDFs were combined with ambient stream flow and quality in a mass balance to generate expected stream concentrations in the form of cumulative distributions functions (CDFs). The final stream concentration CDFs were used to evaluate the probabilities of exceeding instream standards at various locations during a specific storm event.

1 INTRODUCTION

The Silver Bow Creek / Butte Area NPL site encompasses the majority of the historic Butte Mining district where metals mining has been conducted on a large scale for over a century. The site consists of former mining, milling, smelting, and related facilities and associated waste rock dumps, tailings impoundments, mill and smelter wastes, and contaminated soils within and surrounding the populated areas of Butte and Walkerville, Montana (CDM 1990). Surface water in Silver Bow Creek (SBC), the receiving stream at the site, is impaired as a result of impacts from mining-related waste materials and from urban discharge (DEQ 1998). Elevated concentrations of metals leached and eroded from mining-impacted soils and waste materials, as well as channel alterations and industrial and municipal point source discharges, have impaired water quality within the creek such that populations of fish and other aquatic species are very low to non-existent.

A preliminary remedial action objective for SBC is to return the creek to its beneficial uses, which includes providing protection of aquatic communities from direct contact with and/or ingestion of site-related contaminants. SBC is greatly impacted by stormwater runoff from the Butte Hillside adjacent to the upstream end of the creek. Therefore, to meet remedial goals, episodic stormwater runoff events will need to be controlled so that acute in-stream water quality exceedances within SBC are prevented to the greatest extent practicable.

This paper describes a modeling approach implemented to predict acute instream copper (Cu) and zinc (Zn) concentrations resulting from stormwater runoff under specified storm conditions and to evaluate the effectiveness of existing and planned Best Management Practices (BMPs). Copper and Zn were selected for modeling because aquatic organisms are sensitive to elevated concentrations of these two metals; however, the modeling approach is applicable for any contaminant in stormwater. The approach involved using stochastic methods to incorporate the un-

certainty associated with measured stormwater quality data. Specific objectives of this investigation (CDM 2000) were to (1) model instream concentrations in SBC for three 24-hour design storms (2, 5, and 10 year), (2) compare predicted concentrations with and without existing BMP controls, (3) evaluate and prioritize target areas for future BMPs, and (4) identify and evaluate significant modeling data gaps to guide subsequent sampling plans.

2 SITE BACKGROUND

The Silver Bow Creek / Butte Area NPL site encompasses approximately 85 square miles (mi²). The area targeted in this study (Figure 1), which covers an area of approximately 5 mi², is a sub-region of this larger site and encompasses the town of Walkerville, the part of Butte just north of the initial reach of SBC.

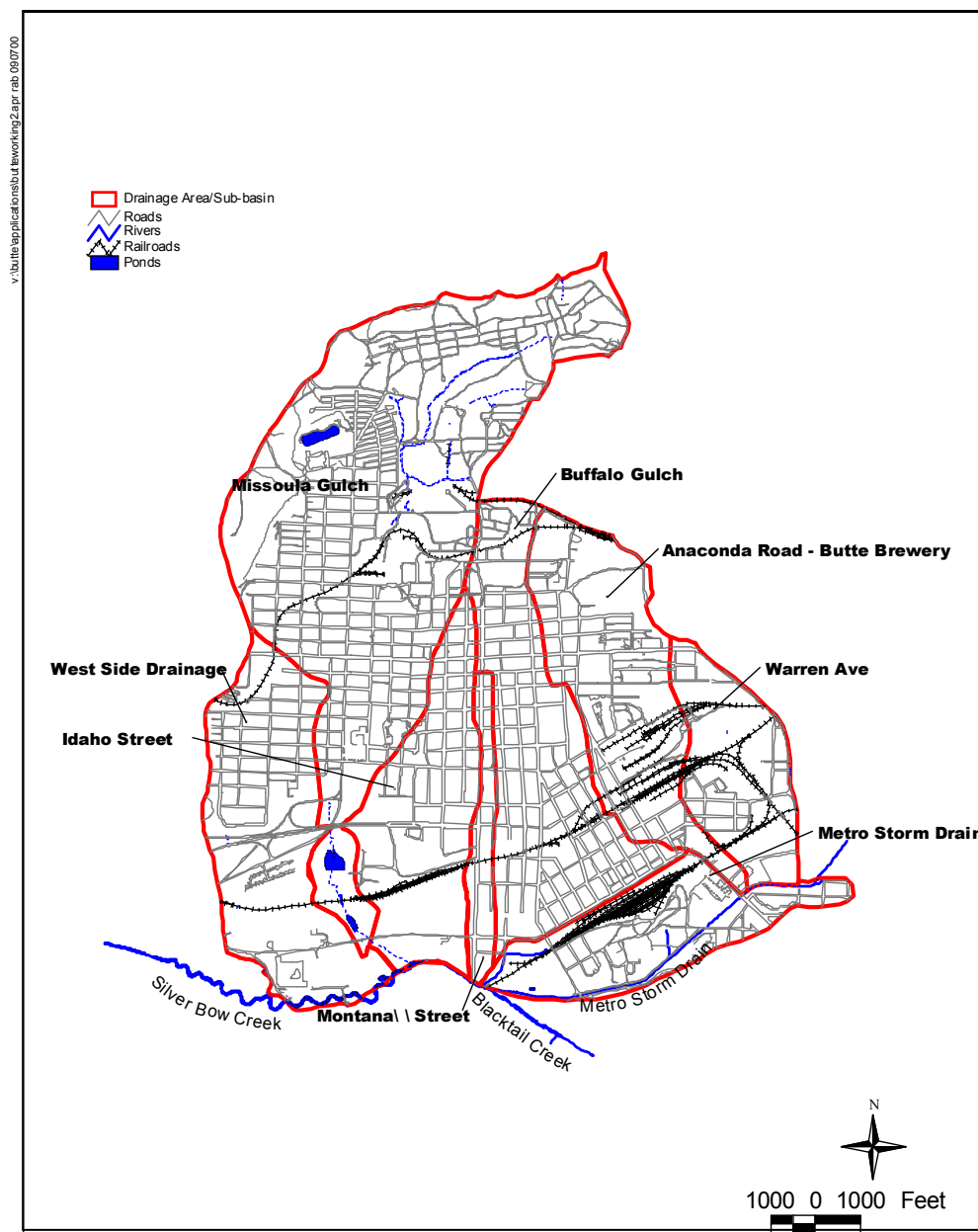


Figure 1. Butte hillside location map.

SBC is a small mountain stream with low to moderate discharge during normal flow conditions (18 - 23 cubic feet per second [cfs]) relative to the potential volume of stormwater runoff

(e.g., 477 cfs for the 10-year, 24-hour peak flow [ESA 1998]). The effective drainage area of SBC is approximately 103 mi². SBC originates at the confluence of the Butte Metro Storm Drain and Blacktail Creek. The Metro Storm Drain is an open channel that was constructed in the early 1930s. The upper portion of this drain is dry except during storm runoff or snowmelt events while the lower portion receives flow via ground water discharge and, during normal flow conditions, contributes between 0.3 and 0.5 cfs to SBC. The primary source of flow in SBC is inflow from Blacktail Creek, which originates in the Highland Mountains and has a drainage basin area of approximately 95 mi². Blacktail Creek normally contributes 11 to 15 cfs to SBC. The Metro Storm Drain and SBC receive flow from several sub-drainage basins on the Butte Hillside during stormwater runoff and snowmelt, including Warren Avenue (Warren), Anaconda Road/Butte Brewery (Anaconda), Buffalo Gulch (Buffalo), Missoula Gulch (Missoula), Montana Street (Montana), Idaho Street (Idaho), and West Side (West Side).

In addition to the perennial stream flow and stormwater runoff, SBC receives regulated discharge from the Butte Metro Waste Water Treatment Plant (WWTP) of between 5 and 9 cfs. Additionally, Lower Missoula Gulch intercepts shallow groundwater and maintains a baseflow discharge to SBC of 0.1 to 0.3 cfs (ESA 1999). BMPs have been implemented in the past five years in the area and include a combination of engineered controls (catch basins, channels, culverts, etc.) and reclamation practices (grading, soil covers, erosion control fabric, etc.).

3 STORMWATER RUNOFF MODELING

Stormwater runoff modeling was performed to predict runoff from the Butte Hillside sub-basins discharging to SBC under varying storm conditions. The model was based on the HEC-STORM model algorithm. The model uses the rational method to predict runoff at hourly timesteps from a given watershed for a given storm event, $Q = CIA$, where Q = runoff flow (cfs), C = runoff coefficient (an empirical coefficient that captures the ratio of expected runoff to precipitation and is dependent on watershed characteristics), I = rainfall intensity (in/hour), and A = drainage area (acres). The model also tracks available depression storage (ponding volume from small depressions throughout the drainage area) and subtracts out a corresponding abstraction (as the depression storage fills up) at each timestep. Use of this model to predict runoff hydrographs is generally valid only for small urban watersheds where the time of concentration (the time it takes runoff from the uppermost portion of the watershed to reach the discharge point) is small.

Runoff coefficients (C) and depression storage (inches) for each sub-basin were calculated from land-use characteristics and assumed percent imperviousness values for the various land-use categories. Sub-basins were delineated for both pre-BMP (prior to the start of BMP implementation about five years ago) and post-BMP (existing basin) scenarios to be modeled.

Twenty-four hour design storms at 2, 5, and 10 year recurrence intervals were selected for modeling. The storm hydrographs were calculated using a Type 2 distribution of precipitation totals taken from the Precipitation Intensity Frequency Atlas for Montana (NOAA 1988), as shown in Figure 2. These storms were input to the model at hourly timesteps and show the greatest intensity in the first hour and decrease in intensity in subsequent hours.

The major BMPs were incorporated in the model (for the post-BMP scenarios) through diversions in the runoff flow, reductions in drainage areas, land-use alterations, and explicit modeling of the detention pond system constructed in the Missoula Gulch sub-basin. The model simulates runoff inflow captured by the ponds, and overflow and controlled outflow from each pond. The overflows and controlled outflows add to the uncaptured basin runoff and discharge to SBC.

4 STATISTICAL ANALYSES OF STORMWATER QUALITY DATA

Statistical analyses of Cu and Zn concentrations (dissolved and total) were conducted to determine the input variables for both pre and post-BMP models. Statistical results indicated that Cu and Zn concentrations for the model inputs were lognormally distributed. Therefore, natural log transformed data were used to generate geometric means and geometric standard deviations for use in the stochastic modeling. For sub-basins with insufficient data for statistical analysis, sto-

chastic input parameters were estimated from other sub-basins with similar land-use characteristics.

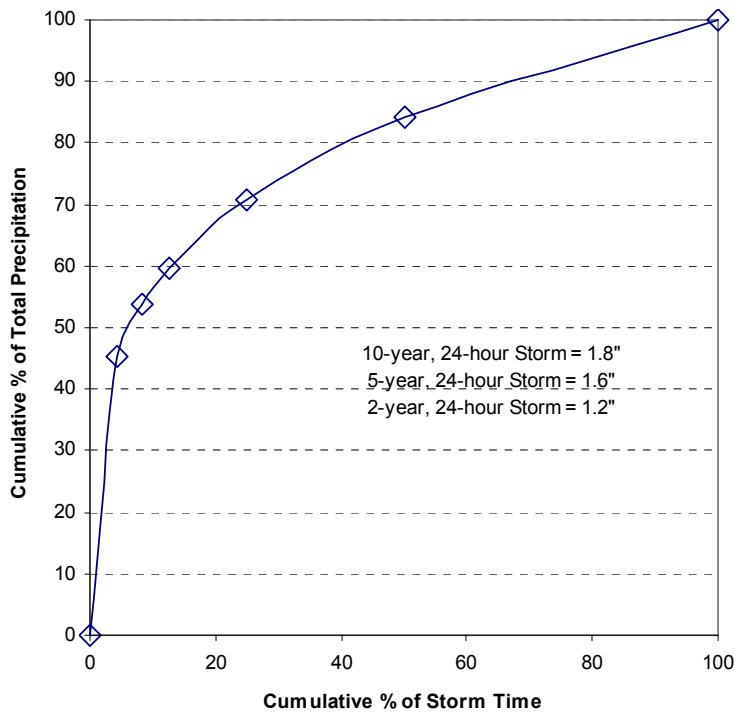


Figure 2. Type 2 design storm.

Statistical analyses were also conducted to identify data correlations between the various sub-basins. This analysis was limited to stormwater data pairs, i.e., samples collected on the same day from two or more sub-basins. The resulting sets of correlation coefficients were averaged to obtain a single correlation coefficient for use in the model. The use of correlations in this manner is based on the assumption that concentrations among the sub-basins for a particular storm event will be related. For example, if concentrations at a particular sub-basin are relatively high, concentrations at all other sub-basins will also be relatively high.

5 STOCHASTIC PREDICTIONS OF INSTREAM CONCENTRATIONS

Due to the uncertainty associated with measured stormwater concentrations, with respect to both the large standard deviations and the timing of sampling and storm events, a stochastic approach was utilized to simulate runoff loadings and resulting acute SBC concentrations. The @Risk addin program to Microsoft Excel was used in conjunction with the runoff model and the water quality statistical analyses. @Risk is a stochastic modeling tool that incorporates and quantifies the uncertainty of specified input parameters by using Monte Carlo simulations to run a given model for a large number of iterations while randomly sampling input probability distributions for each stochastic parameter at each iteration. The resulting output variables are presented in the form of CDFs of expected values.

The SBC model was set up as a stream mixing spreadsheet where 24-hour stormwater hydrographs are combined with assumed upstream and groundwater flow and concentration conditions to calculate expected downstream concentrations. The model assumes instant and complete mixing in the stream. For each simulated storm event (2, 5, and 10 year 24-hour storms) runoff hydrographs were determined for each sub-basin externally using the runoff model. These hydrographs were then used as the flow inputs to the mixing model. The PDFs for stormwater and groundwater concentrations at each sub-basin were input as stochastic variables to the instream model. Correlation coefficients between each of the sub-basin PDFs were also input.

During a given simulation, the model, at each timestep, randomly sampled the sub-basin PDFs (incorporating the appropriate correlations) to generate stormwater/groundwater concentrations. These concentrations were combined with the runoff flows and mixed with ambient stream conditions to generate instream concentrations throughout the reach of interest. This process was repeated thousands of times within a given simulation. The model output was in the form of CDFs that predict 24-hour average instream concentration exceedance probabilities at selected points along SBC. Figure 3 summarizes the modeling process.

Separate simulations were performed for each of the contaminants of concern, for each of the three storm events (2, 5, and 10 year), and for each of the two site characteristic scenarios (pre and post BMP conditions).

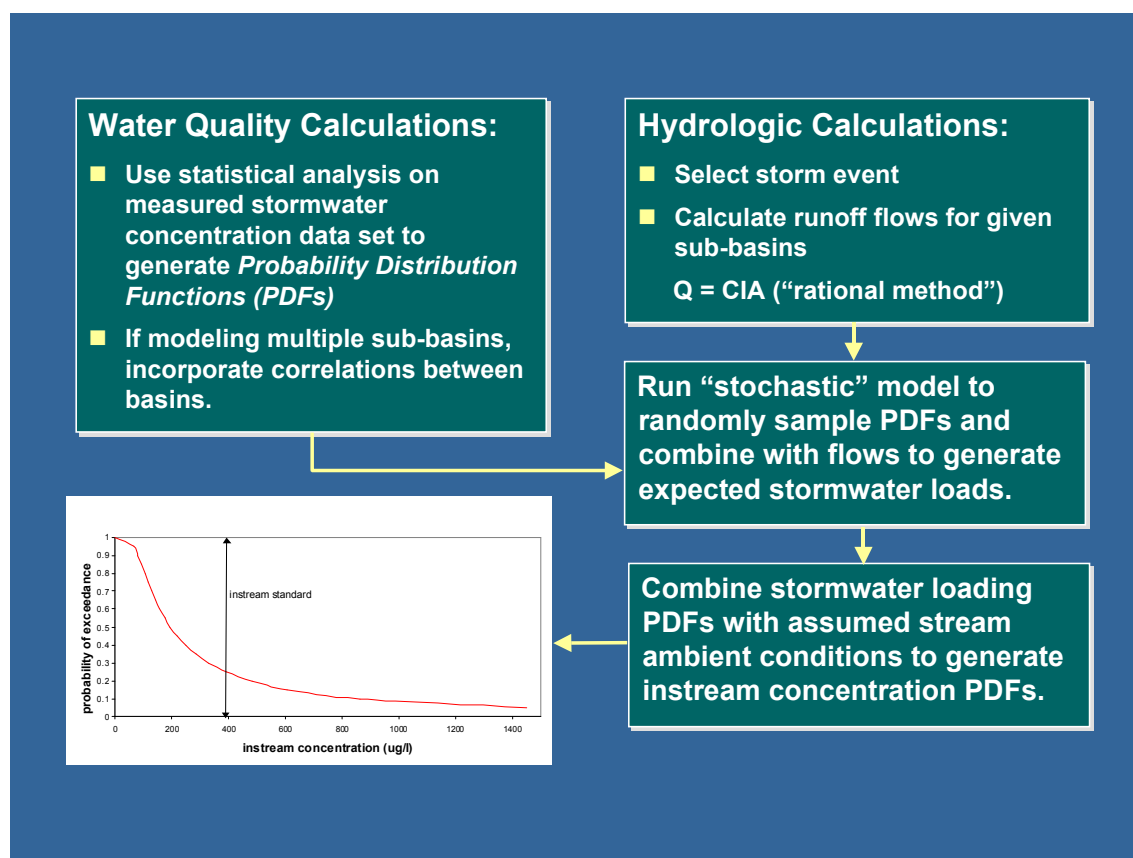


Figure 3. Stochastic modeling overview.

6 RESULTS AND DISCUSSION

6.1 Predicted Instream CDFs

Figure 4 shows an example CDF generated by the stochastic model, in this case for instream total Zn concentrations at the furthest point downstream in the SBC reach of interest. Included on Figure 4 are CDFs for pre and post BMP model results under each of the three simulated storm events. As an example of how to interpret the CDFs, an exceedance probability of 0.4 represents a 40% chance of exceeding the corresponding concentration as a 24-hour average for the given storm event. Histogram distributions of measured total Zn concentrations are provided for comparison with the modeled CDFs.

The results shown in Figure 4 indicate that significant improvements in predicted total Zn concentrations have likely occurred following BMP implementation, e.g., about a 35% reduction in the 20% exceedance concentration. The results also indicate that differences in total Zn concentrations due to varying magnitudes of storm events are very small. Furthermore, while measured total Zn concentrations fall within the CDF ranges predicted by the model, they tend to cluster near the lower concentration end, indicating the influence of sample collection during ambient rather than storm event periods. Similar results were obtained for dissolved Zn and total and dissolved Cu.

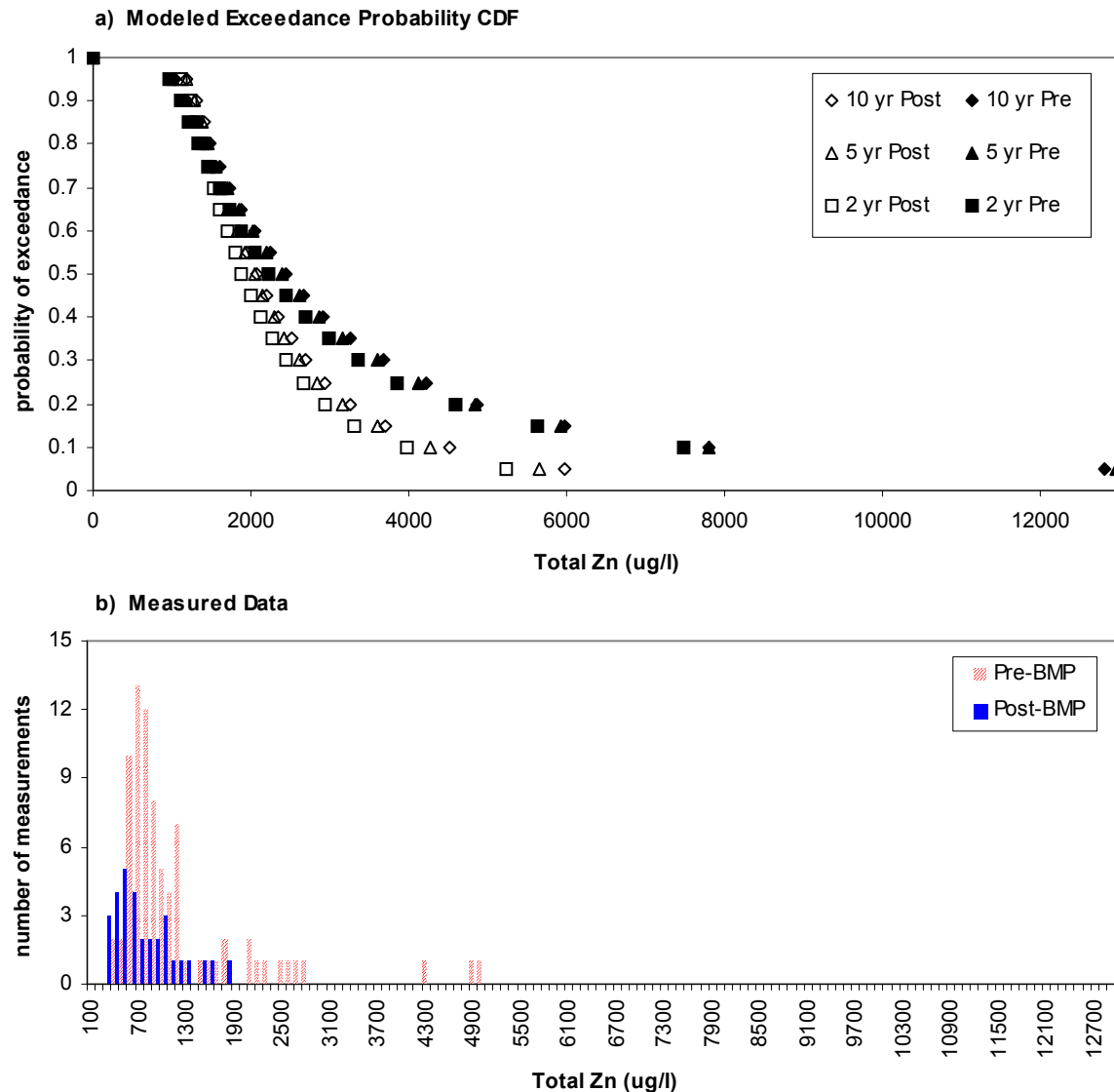


Figure 4. Modeled and measured results for Silver Bow Creek.

6.2 Model Sensitivity Analyses

To further evaluate model uncertainty, three key non-stochastic model parameters were investigated in terms of model sensitivity: groundwater inflow, Blacktail Creek flow (upstream steady flow), and the correlation coefficient matrix. The uncertainties associated with these model inputs were not captured in the stochastic approach. For each of these parameters, the model input values were varied over a reasonable range and the resulting instream CDFs were compared to the original modeled results. Groundwater inflows, which were included as steady flows in the instream mixing model at both the Missoula Gulch outfall and as a portion of the Metro Storm Drain contribution, and the Blacktail Creek upstream flows were varied $\pm 100\%$ during the sen-

sitivity analysis. The correlation coefficient matrix was varied from 0.0 to 1.0. Total copper at the most downstream location on SBC was predicted for the 10-year storm, post-BMP scenario.

The results of the sensitivity analyses indicate very little model sensitivity to groundwater flow (Figure 5) and a slightly higher sensitivity to the correlation coefficient matrix (Figure 6), with exceedance concentration differences reaching as high as +19% but generally below $\pm 15\%$. The model was most sensitive to Blacktail Creek flow variations (Figure 7), with modeled concentration differences of approximately $\pm 20\%$ throughout most of the distribution. The sensitivity to Blacktail Creek is expected as the Blacktail Creek headwater flow is a primary dilution factor in the model. The flow value used in the stochastic modeling represents a conservative assumption of baseflow conditions in Blacktail Creek. Increased upstream flow in Blacktail Creek due to storm conditions was not incorporated into the scenarios modeled here but could easily be altered for future uses of the model.

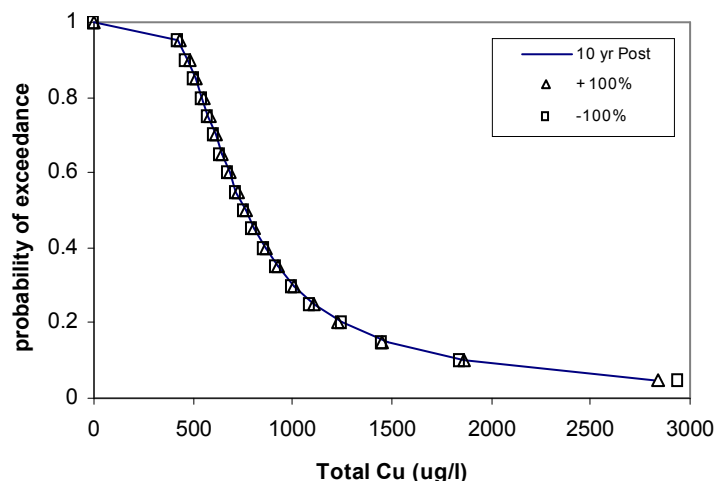


Figure 5. Groundwater flow sensitivity for 10-year, 24-hour storm.

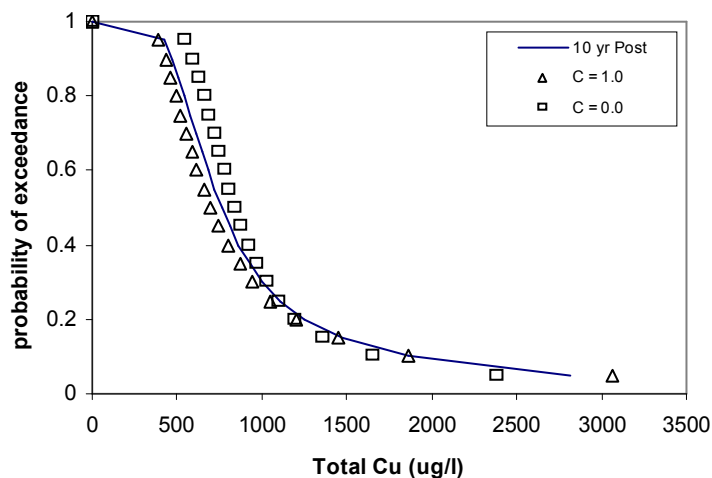


Figure 6. Correlation Coefficient sensitivity for 10-year, 24-hour storm.

6.3 Future BMP Implementation

To help guide future BMP implementation, the impacts of individual sub-basin loading removals on instream concentrations were evaluated. The post-BMP model was modified by removing loads one sub-basin at a time and comparing the new predicted 50% exceedance concentration with the original model concentration for the 2-year storm. Groundwater and the wastewater treatment plant effluent loads were also included in this analysis. These types of

simulations only allow for the comparison of relative effects of *isolated* loading removal rather than of any combined loading removal.

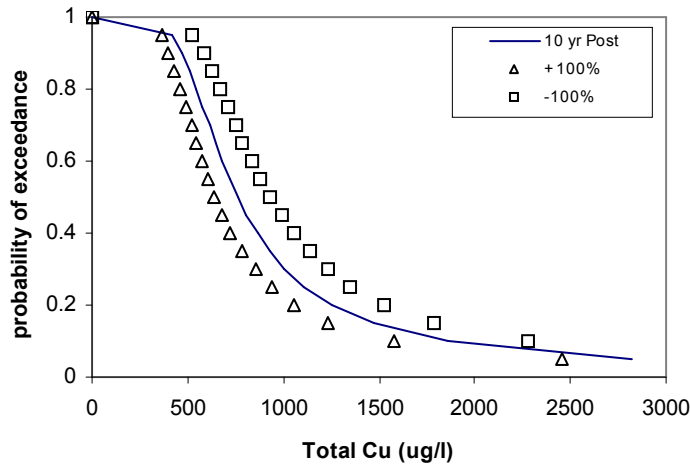


Figure 7. Blacktail Creek flow sensitivity for 10-year, 24-hour storm.

Concentrations at the downstream-most station on SBC were analyzed. Figure 8 represents an example of the results for dissolved Cu. As shown, individual removals of the Warren, Anaconda, and Missoula sub-basins (both surface water and groundwater for Missoula) resulted in percent dissolved Cu reductions ranging between about 7 and 12%, indicating that these sub-basins would be good areas to focus future BMP efforts. Note that removal of the WWTP discharge results in a negative percent reduction (or increase) because it represents a dilution component for dissolved Cu.

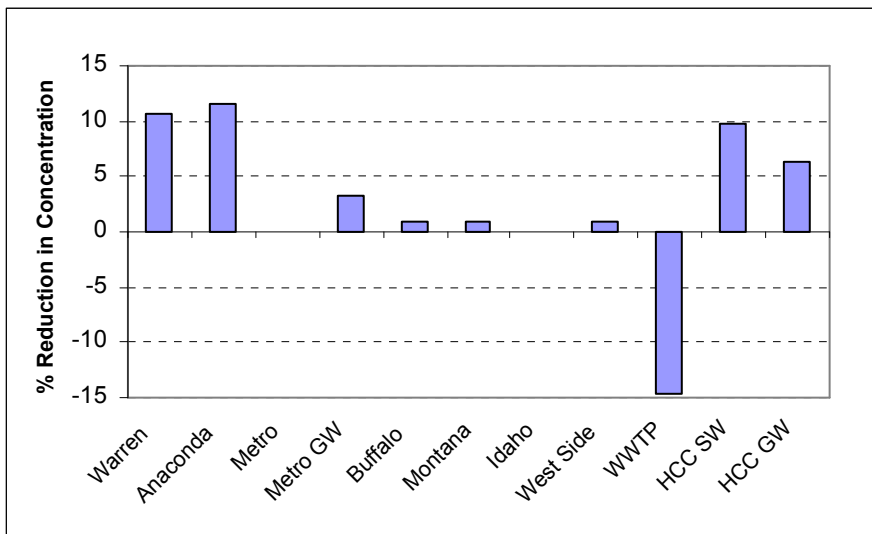


Figure 8. Effects of isolated sub-basin loading capture on Silver Bow Creek dissolved Cu concentration. HCC SW is Missoula surface water and HCC GW is Missoula groundwater.

6.4 Model Limitations

The ability of the stochastic model to accurately predict SBC water quality depends on the quality of the data input variables. There are several limitations of the current model that warrant further characterization. First, the stochastic approach relies on measured data and model accuracy is limited by the quality and quantity of the data. For this case study, data gaps were filled by assuming similar concentration distributions between sub-basins with similar land-use char-

acteristics. Second, a constant correlation coefficient was used for all sub-basins despite the fact that the value most likely varies between sub-basin pairs. Third, the current model does not include a component for storm-induced re-suspension of contaminated sediments contained in SBC. Finally, the impacts of reclamation BMPs in certain sub-basins were not incorporated into the current model. In particular, only loading reductions due to flow capture and diversions were incorporated in the current model, whereas BMPs that may have reduced storm water concentrations were not. With adequate post-BMP concentration data, reclamation BMPs could easily be included.

7 SUMMARY AND CONCLUSIONS

The stochastic approach to modeling stormwater and receiving stream concentrations at the Butte hillside proved useful for characterizing the uncertainty associated with stormwater quality data. This approach enabled prediction of SBC water quality resulting from various storm events, evaluation of critical data needs, and characterization of the impacts of BMPs implemented at the site. Most importantly, the model provides a tool for guiding subsequent data collection, so that future BMP activities can be focused to provide maximum benefit. This approach is considered extendable to similar mining waste sites where stormwater runoff is impacting stream water quality.

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